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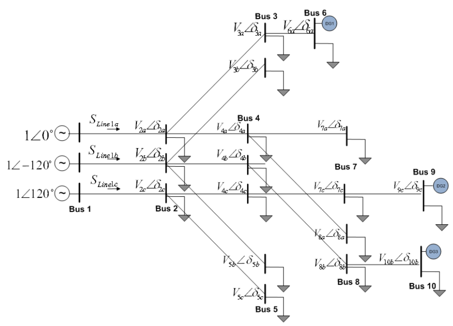


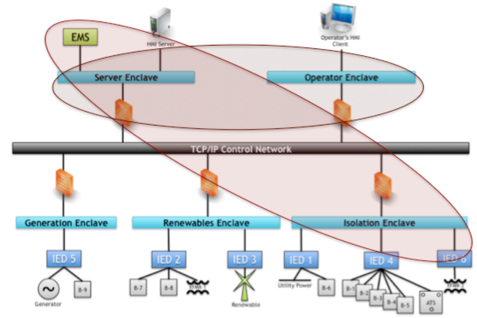



# SPIDERS Microgrid Design Analysis Approach for NASA White Sands Test Facility

2014 International Workshop on Environment and Alternative Energy
Kennedy Space Center, Florida
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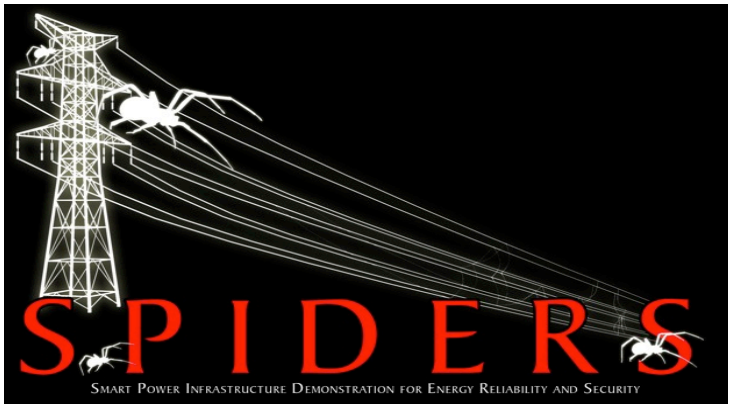
# Sandia's Proven Experience with Defense Energy Security Challenges and Projects

Sandia National Laboratories

| Energy Surety Assessments & Microgrid Conceptual Designs | Small Scale Demos | Large Scale Demos | Operational Energy Modeling, Analysis & Optimization |
|---|---|---|---|
| • Philadelphia Navy Yard – new FY11, DOE OE<br>• Camp Smith – completed FY10, DOE FEMP<br>• Indian Head NWC – complete FY10, DOE OE<br>• Ft. Sill – completed FY07, LDRD<br>• Ft. Bliss – Phase 1 completed FY10, DOE FEMP<br>• Ft. Carson – Nearing completion, DOE FEMP<br>• Ft. Devens (99th ANG) – Conceptual design complete, DOE OE/DoD<br>• Ft. Belvoir – Prelim design done, DOE OE/ FEMP<br>• Cannon AFB – New FY11<br>• Vandenberg AFB – Initial site visit complete, DOE FEMP<br>• Kirtland AFB – Assessment DOE OE<br>• Maxwell AFB – Conceptual design complete, demo underway<br>• Creech AFB – Joint Energy and Physical Security Assessment – FY12<br>(Integrated Mission Assurance Pilot)<br>• SOUTHCOM – Soto Cano ESM Project – FY12/FY13 (SNL & NREL)<br>• OSD ATL OEPP – Bagram, Afghanistan – FY13 (SNL & NREL)<br>• ASAI&EE – Microgrid Lessons Learned FY13-FY14 | • Maxwell AFB – DOE OE/ Mostly DoD<br>• Ft. Sill – SNL tech advisor<br>• Base Camp Integration Lab (BCIL) at Ft. Devens – Expeditionary Energy Storage System (EESS) Demo FY12-FY14 | • SPIDERS JCTD FY11-FY14<br>– Joint Base Hickam<br>– Camp Smith<br>– Ft. Carson<br>(SNL, NREL, INL, PNNL & ORNL) | • Ground Combat Systems Energy Efficiency KPP Analyses FY11-FY14<br>• Contingency Basing (e.g., FOBs) Architectures and Assessments FY12-FY14<br>• Joint Operational Energy for Ground Systems, FOBs & Warfighters FY12-FY14<br>• USMC Expeditionary Energy Office FY12-FY14<br>• Base Camp Integration Lab (BCIL) at Ft. Devens M&S FY12-FY14<br>• Army Operational Energy Task Force OSD OECIF FY14 New Start |

# SPIDERS Project Summary

- SPIDERS (Smart Power Infrastructure Demonstration for Energy Reliability and Security) is building three microgrids, each with increasing capability, which will function as permanent energy systems for their sites
  - Site 1 (Joint Base Pearl Harbor Hickam) is complete
  - Site 2 (Fort Carson) is complete
  - Site 3 (Camp Smith): completed preliminary design, demo in FY15
- The project will promote adoption of microgrid technology for DoD through:
  - Design and requirements methodology
  - Cyber security architecture



# SPIDERS JCTD Overview

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### PEARL HARBOR / HICKAM AFB CIRCUIT LEVEL DEMONSTRATION

- Renewables
- Storage
- Energy Management

### FT CARSON MICRO-GRID

- Large Scale Renewables
- Vehicle-to-Grid
- Large scale storage
- Critical Assets
- Demonstration to tie in with COOP Exercise

### CAMP SMITH ENERGY ISLAND

- Entire Installation Smart Micro-Grid
- Islanded Installation
- High Penetration of Renewables
- Demand-Side Management
- Redundant Backup Power
- Makana Pahili Hurricane Exercise

### TRANSITION

- Template for DoD-wide implementation
- CONOPS
- TTPs
- Training Plans
- DoD Adds Specs to GSA Schedule
- Transition to Commercial Sector via DOE
- Transition Cyber-Security to Federal Sector and Utilities

### CYBER-SECURITY

# ESM Load Categorization

- Tier C – loads / buildings that are critical to the mission; these loads usually have dedicated backup generators. Tier $C_U$ loads are non-interruptible and will include UPS, while Tier $C_I$ loads can endure short losses of electrical power.
- Tier P – loads / buildings that are nice to have, but that can be switched on or off the microgrid at the base commander's discretion. Some of these loads may have dedicated backup generators. Some may be designated ahead of time, while others might be promoted ad hoc (depending on their configuration).
- Tier O – loads / buildings that will not be powered during microgrid operations.
- Tier $O_P$ – loads that are too small to merit the cost of automation (e.g. streetlights or parking lights).

# Energy Surety Microgrid: How it Works

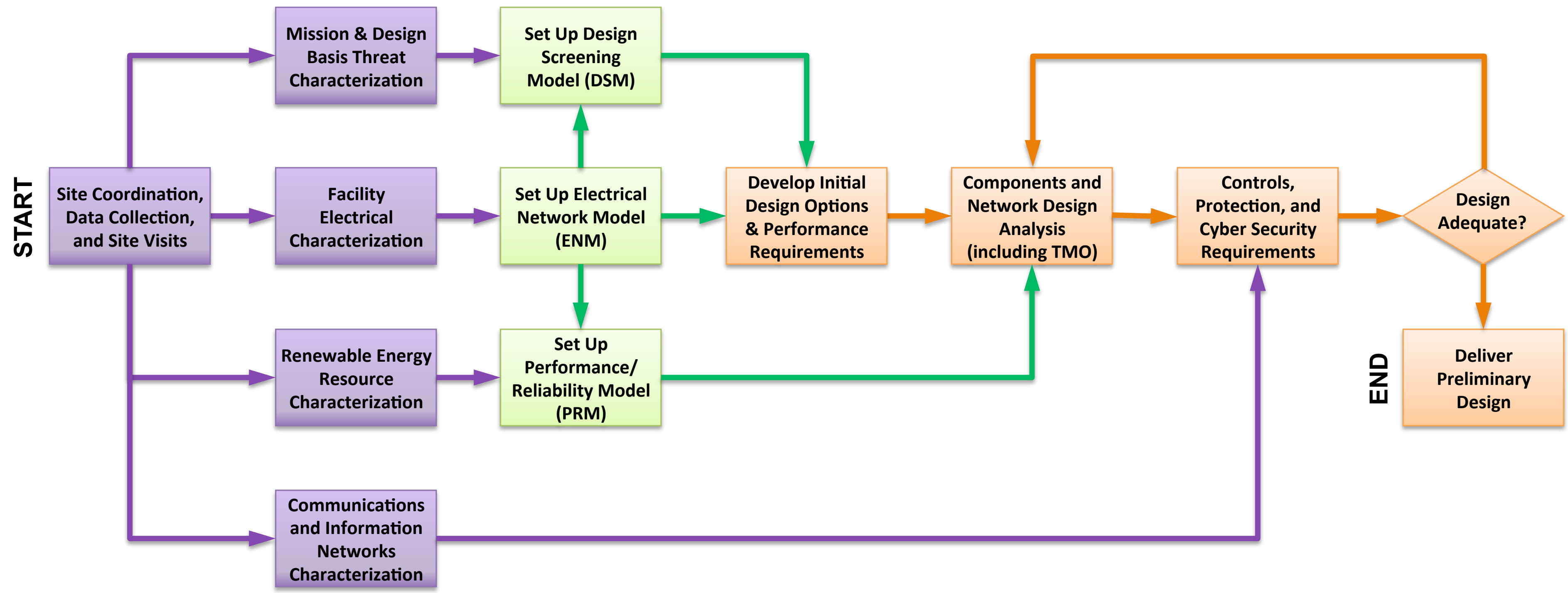
- When utility power is unexpectedly lost, normal backup operations occur (an ESM does not preclude traditional, accepted engineering practice)
- During an outage, UPS carry non-interruptible critical loads as the microgrid disconnects from the utility and the diesels start
- Architecture reconfigures the existing medium voltage (MV) network to create a microgrid backbone
- Connections for existing diesels are changed to allow simultaneous connection to critical building loads and also the MV network (additional energy assets can be added, but an ESM does not require a new central plant)
- The diesels are synched together on the MV microgrid network, and any other additional sources (like renewable energy) are brought online
- Tier P loads may be served as feasible and useful
- ESM is built so that emergency generators can be returned to conventional connections and operation if needed – do no harm

***ESM reuses existing equipment to support mission energy security***

# ESM’s/SPIDERS Microgrids Support Seven Key Value Propositions

1. **Improve reliability** for mission-critical loads by connecting generators on a microgrid using existing distribution networks.
2. **Increase endurance for backup energy during outages** by using renewable energy sources and increased efficiency of generators.
3. **Improve maintenance capabilities** by allowing for necessary downtime of diesel generators during extended outages without interruption of service, as well as enabling full-load testing of machinery grid-connected.
4. **Reduce operational risk** for energy systems through a strong cyber security for the microgrid.
5. **Enable flexible electrical energy** by adding capability to selectively energize loads during extended outages.
6. **Improve energy situational awareness** through always-sensing control system.
7. **Reduce energy costs** during normal operations by controlling microgrid resources to lower consumption / demand charges, and also generate ancillary services revenue.

# SPIDERS/ESM Technical Approach

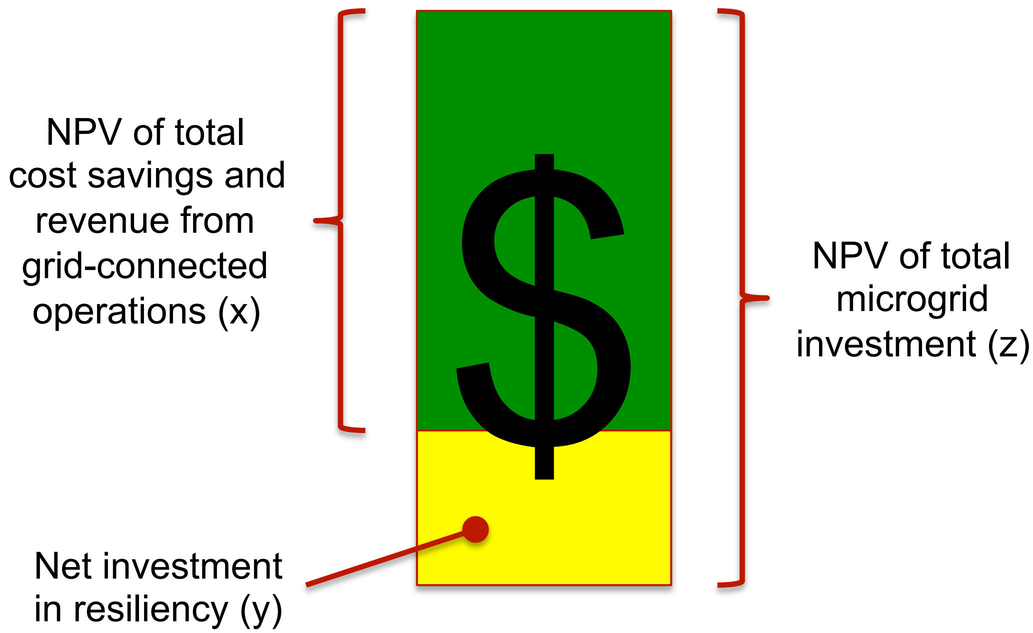



- **Design Phase**
  - **Conceptual design – What are the microgrid requirements and what energy assets are needed?**
  - **Preliminary design – What are the microgrid functional requirements? How do we control and secure it?**
  - **Detailed design – Create a buildable construction specification, teaming with industry.**
- **Installation and Testing**
- **Operation and Transition**

# Microgrid Resiliency Analysis Example

- Here, $x + y = z$
- The benefits of resiliency improvements are difficult to think of in terms of dollars
- However, if investments are considered as shown to the right, stakeholders have a simple question:

  **Are the benefits worth the investment *y*?**



# Design Decisions Basis

- Design Screening Model (DSM)
  - Use of systems dynamics modeling or other analysis and engineering judgment
  - Narrow microgrid design options
  - Investigate key relationships between building load, PV generation, and diesel electrical generation
- Electrical Network Model (ENM)
  - Ensure voltage magnitudes remain close to rated values despite changes to feeder configurations
  - Determine if the feeder has adequate capacity to carry the additional new generation
- Performance/Reliability Model (PRM) using TMO (Technology Management Optimization) software
  - Used to optimally determine several design parameters for the the three SPIDERS microgrid
  - Optimally manage high-value, long-lived, highly technical equipment over the lifetime of a system

# Performance/Reliability Model (PRM)

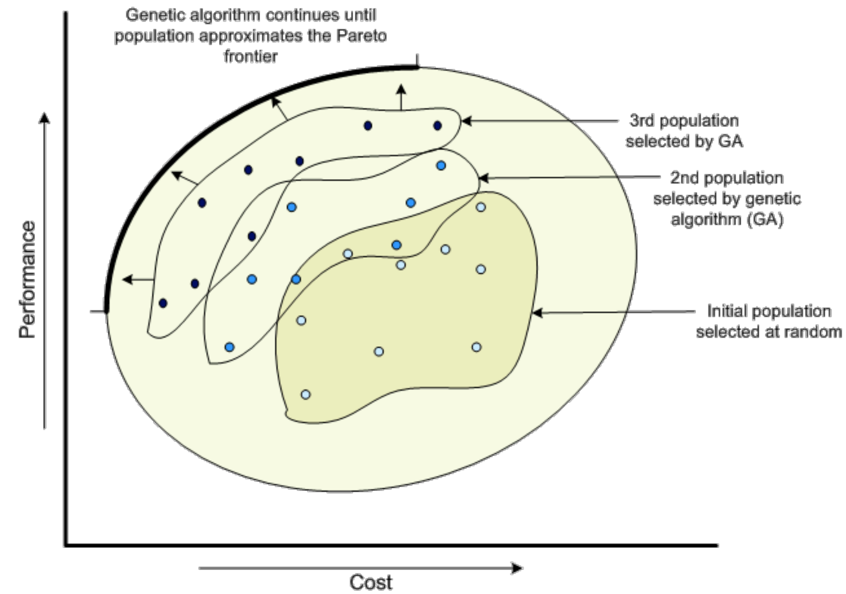
- The purpose of the PRM is to statistically quantify the behavior of a candidate microgrid design in terms of performance and reliability
- This information is used by TMO to tune the design according to the design options in order to maximize performance and reliability while minimizing cost
- PRM operation:
  - Samples utility outages according to a distribution (e.g. at a rate of ~4/year) for thousands of years
  - Microgrid is simulated during each outage and statistics are collected
  - Uses an event-driven simulation for better calculation efficiency
  - Once the standard error of the mean (SEM) of the primary statistic is below the desired threshold, the simulation stops and returns the analysis
- Required Information:
  - Electrical layout, including transmission/distribution line data
  - MTTF and MTTR for grid elements, transmission lines, other relevant equipment
  - Generator efficiency curves and other data
  - Load profiles (both critical and priority)
  - PV and wind profiles, etc.

# Optimizing Microgrid Design Performance

## TMO

•Calculates fitness of design based on statistics from PRM
•Keeps track of the solutions (sets of design parameters) with the greatest overall fitness
•TMO develops the set of Pareto optimal points (multi-objective solution)

**Design Parameters from TMO to PRM**



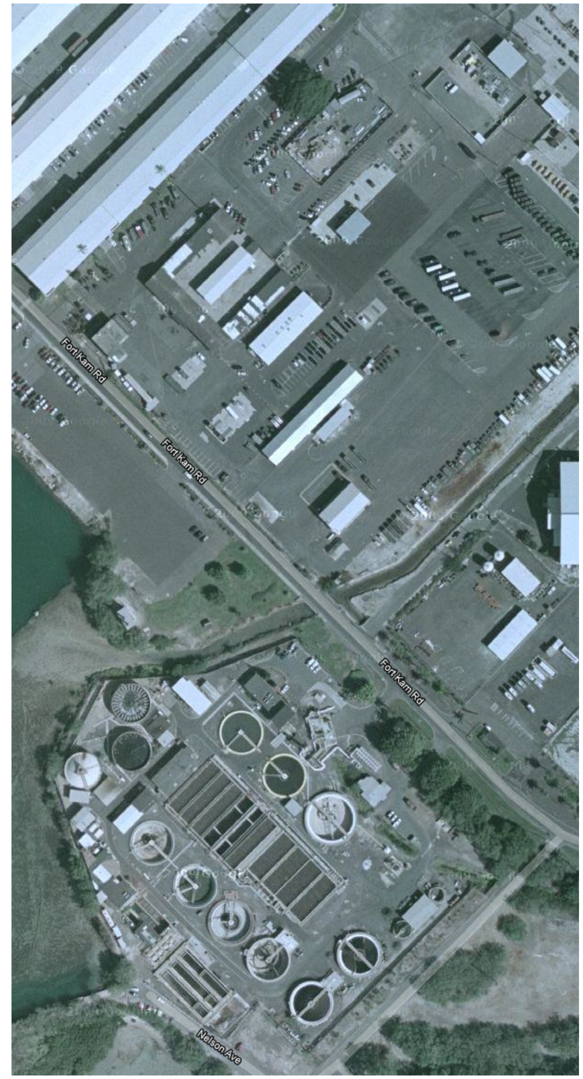

## Reliability/Performance Model (PRM)

•Event based simulation
•Calculates statistics of interest based on candidate design parameters from TMO

**Statistics of Interest from PRM to TMO**

# Phase 1: Hickam AFB Status

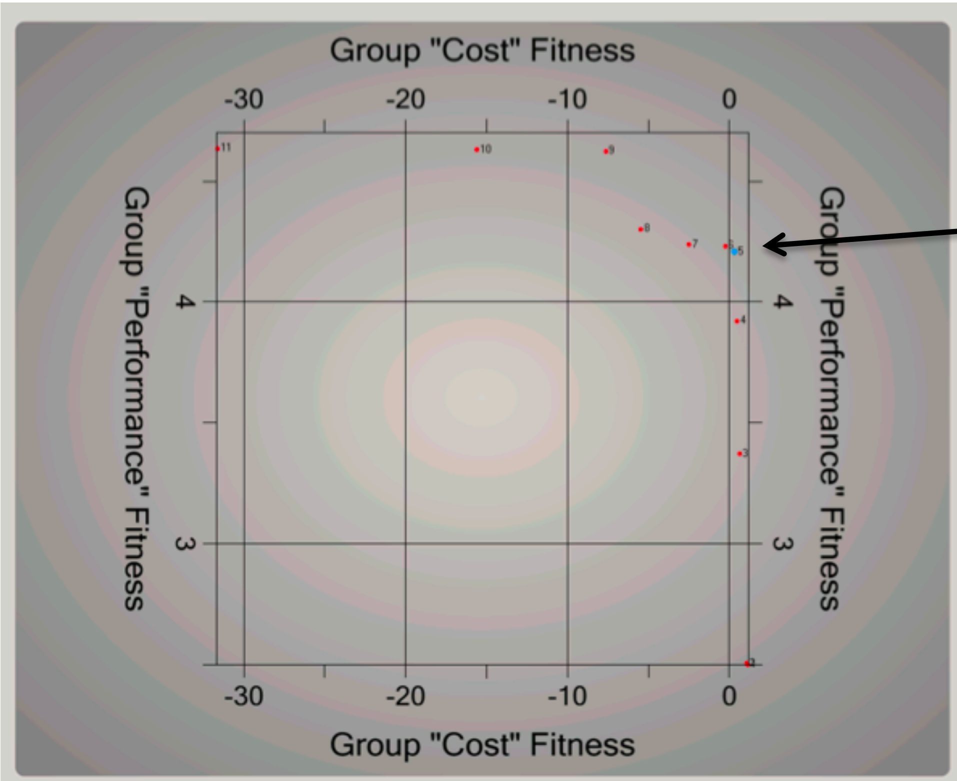
- 100% design complete, contracting by USACE
- Single feeder microgrid (all load is Tier 1, two diesel engines, photovoltaics, & energy storage)
- Sandia and other DOE labs developed the preliminary design and worked with USACE, the integrator, and their subcontractors
- Operational demonstration in January 2013
- Results show that:
  - System operates as intended
  - Site personnel can manage the microgrid



# Phase 2: Fort Carson Status

- Preliminary design report complete
- Recommendations for:
  - MV and LV topology
  - Renewable energy (PV)
  - Storage size and application
  - V2G for PEVs
- Design charrettes (intensive period of design activity) were held at Fort Carson in March 2012
  - Briefed on DOE design
  - Questions were fielded and documented
- Includes Tier 1, 2, and 3 loads (Hickam was Tier 1 only)
- Final integrator selected
- Requirement for seamless planned transition was successfully added; 100% design is complete
- Construction is complete
- Operational demo in October 2013

# Performance/Reliability Model (PRM)




| Fitness | Tier 1 | Tier 2 | Fossil Generation | PV | Battery/ PHEV |
|---|---|---|---|---|---|
| Perform-ance = 4.231 | Budget allows buildings A-E and H, not F-G | Include all designated (buildings W, X, Y, Z) | Use diesels in buildings A, C, D, and H, but not B or E | PV = 1MW (out of 0, 1, or 2) | Size = 750kW / 250kWh |
| Cost: $1.3M | (Reason: incremental MV cost too high) | Can serve additional non-designated = 1000kW | No added fossil generation (diesel or NG) | (contract-ual limit-ations) | Use: smooth RE & defer diesel switching |

This graph presents the Pareto optimal set of solutions for the Ft. Carson microgrid.

With no Tier 2 load served, the microgrid fuel consumption is approximately 79.6 gal/hr.

| Option | Performance Fitness | Battery Size (kW/ kWH) | % of time CLNS >0 | PLS (kWh/hr of outage | Diesel Redispatch Avoidance | Avg. Diesel Efficiency | Non-Designated Tier 2 Load (kW) | Incremental Cost ($US) | Avg. Diesel Used (gal/hr of outage) |
|---|---|---|---|---|---|---|---|---|---|
| Base Case | N/A | 0/0 | 14.333 | N/A | N/A | 0.2817 | 0 | 300,000 | 102.34 |
| 4 | 3.921 | 500/250 | 0.0232 | 602.38 | 0.0592/hr | 0.3603 | 400 | 1,185,938 | 109.58 |
| 5 | 4.207 | 750/250 | 0.0465 | 1078.37 | 0.0875/hr | 0.3669 | 1000 | 1,279,125 | 142.24 |
| 6 | 4.231 | 1000/250 | 0.0232 | 1078.36 | 0.0879/hr | 0.3670 | 1000 | 1,372,313 | 142.24 |

# Phase 3: Camp Smith

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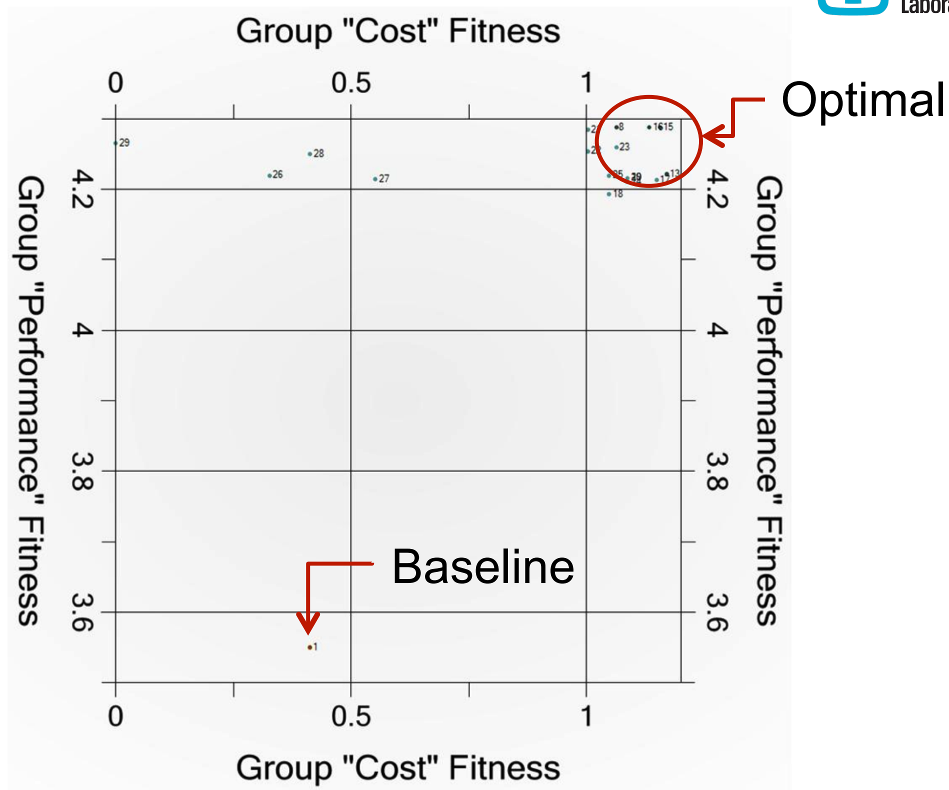
- Microgrid covers the entire installation – capable of serving all loads during outages
- Prior microgrid report from DOE FEMP funding
- Camp Smith includes some older infrastructure which presents challenges
- Include revenue generation/cost avoidance from the microgrid (example analysis at right)
- Demonstration planned for 2015

| Demand Charge | Energy Charge | Onsite Energy Cost | Total Utility Bill | Total Average Costs |
|---|---|---|---|---|
| (Nominal kW) | (Utility MWh) | (Site MWh) | | (Savings) |
| $84,760 | $519,786 | $0 | $604,946 | $604,946 |
| 4036 | 2227 | 0 | | 0 |
| $44,988 | $487,028 | $37,513 | $532,416 | $569,929 |
| 2,142 | 2087 | 140 | | $35,017 |
| $44,988 | $487,028 | $37,513 | $532,416 | $569,929 |
| 2,142 | 2087 | 140 | | $35,017 |
| $57,588 | $503,257 | $18,928 | $561,245 | $580,173 |
| 2,742 | 2156 | 71 | | $24,773 |

# TMO-PRM: Smith

- Pareto chart →
- Availability:

| | | |
|---|---|---|
| Baseline | Tier 1A | 0.995805 |
| | Tier 1B | 0.995341 |
| | Tier 2 | 0.000000 |
| With Tier 2 | Tier 1A | 0.999861 |
| | Tier 1B | 0.999844 |
| | Tier 2 | 0.999808 |
| Without Tier 2 | Tier 1A | 0.999998 |
| | Tier 1B | 0.999976 |
| | Tier 2 | 0.000000 |




- Performance:

| Option | Variable Cost | Avg. Diesel Consumption (gal/hr) | Avg. Gen Efficiency | Average Tier 1 A Not Served (Tier 1 A Outages) (kWh/h of outage) | % of Outages where Tier 1 A Not Served > 0 | Average Tier 1 B Not Served, (Tier 1 B Outages) (kWh/h of outage) | % of Outages (Post-startup) where Tier 1 B Not Served > 0 | Tier 2 Load Served (kWh/h of outage) |
|---|---|---|---|---|---|---|---|---|
| Base Case | $0 | 75.25 | 0.318 | 49.25 | 0.04167 | 37.83 | 0.05984 | 0.0 |
| Option 6 (Highest fitness Solution w/Tier 2) | $1.1M | 111.58 | 0.367 | 17.95 | 0.00378 | 16.60 | 0.00392 | 1275.0 |
| Option 13 (Highest fitness Solution w/o Tier 2) | $1.1M | 56.34 | 0.348 | 0.68 | 0.00109 | 1.57 | 0.00045 | 0.0 |

# Cyber Security: Enclaves/Functional Domains

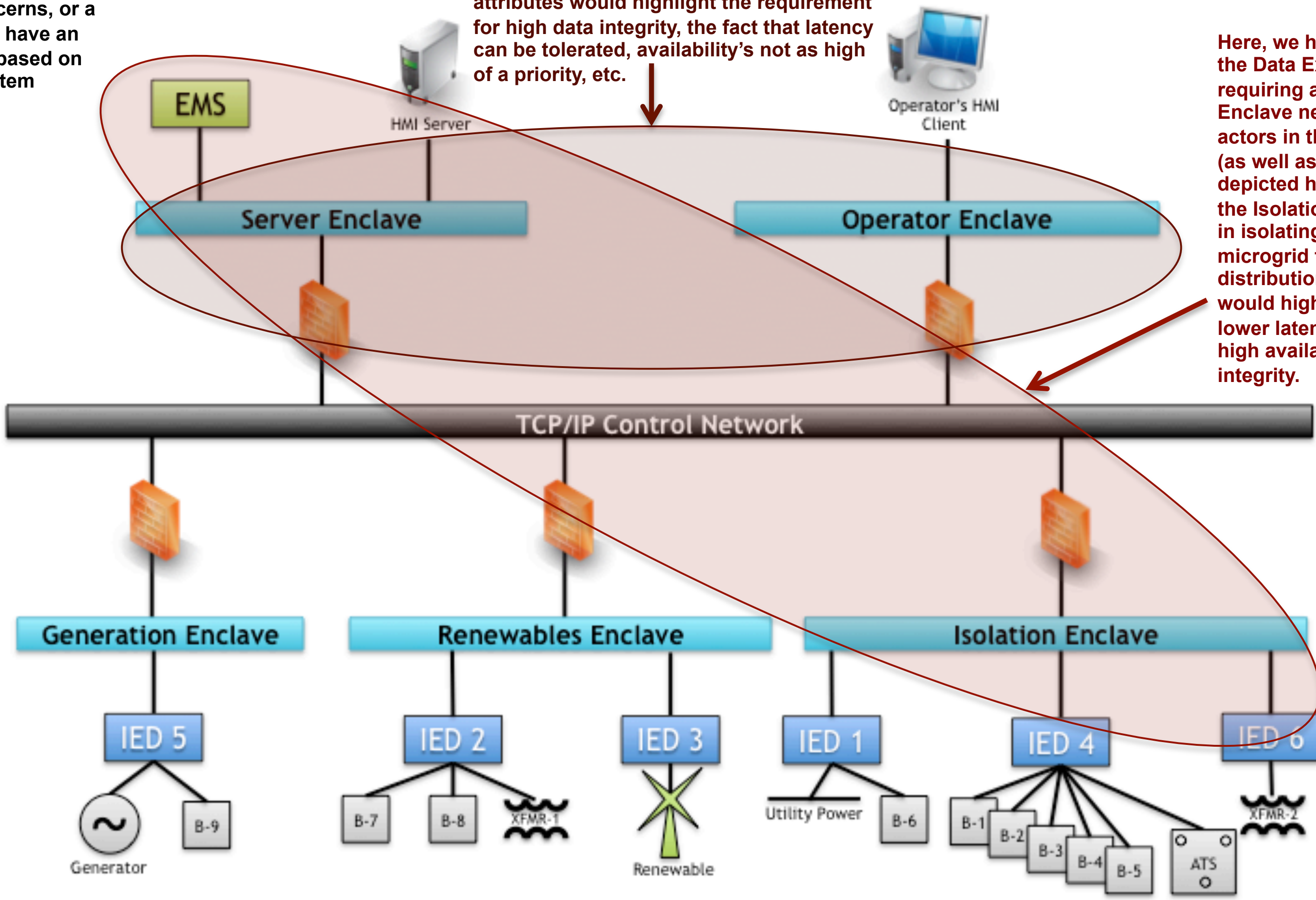
Enclaves can be defined and implemented based on multiple criteria, such as location, function, security concerns, or a combination. Here, we have an example of enclaving based on power and control system device usage types.

Data exchange attributes define how actors need to communicate with one another to support control system functions. This communication can be intra- or inter-enclave.

Functional domains help to identify inter-enclave communication requirements and define how the inter-enclave communication will be supported and secured based on the data exchange attributes.

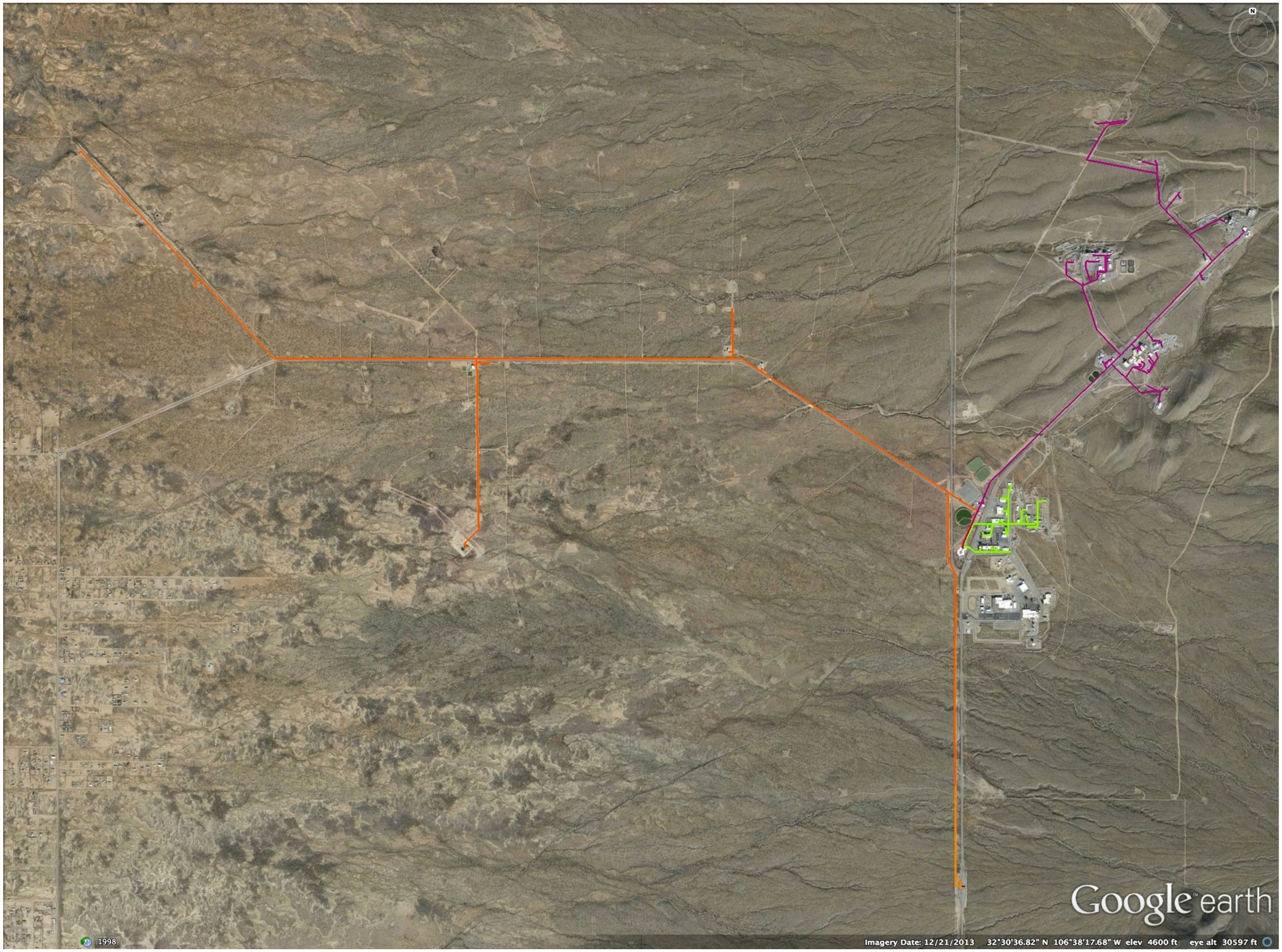
Here, we have an example of the Data Exchange Attributes requiring actors in the Operator Enclave only needing to talk to actors in the Server Enclave. The attributes would highlight the requirement for high data integrity, the fact that latency can be tolerated, availability's not as high of a priority, etc.

Here, we have an example of the Data Exchange Attributes requiring actors in the Server Enclave needing to talk to actors in the Isolation Enclave (as well as other enclaves – not depicted here). Since actors in the Isolation Enclave play a role in isolating the SPIDERS microgrid from the regular distribution grid, the attributes would highlight the need for lower latency requirements, high availability, and high data integrity.




Once the Enclaves and Functional Domains are defined and decorated with exchange attributes as exampled above, they can be used to drive the actual implementation of the control system network. As an example, the definition of each enclave above dictates where firewalls needed to be deployed within the network to logically separate control system actors. The definition and decoration of each domain with exchange attributes dictates how quality of service should be configured for each enclave and between enclaves, which ports need to be opened in which firewalls, for which communication channels authentication and encryption needs to be utilized, etc.

# WSTF Site Overview



# Design Methodology

- Low voltage switches can be used in place of medium voltage switches to bring Tier C and P buildings on to and take Tier O buildings off of the microgrid
- Modeling and analysis geared toward a 72 hour outage
- A dedicated microgrid feeder was considered but not feasible
  - Expensive
  - No future flexibility to add Tier O loads to the microgrid
- Switches will be retrofitted where possible (rather than replaced) to provide automation
- Transformer inrush currents will be managed
- Some ***small*** Tier O loads left on permanently
- Some Tier O loads removed by disconnecting the entire lateral; can't be upgraded later to Tier P loads
- Incorporate existing/planned PV at WSTF to operate during extended outages
- Cost estimates include:
  - MV improvements/switching/remote control/communications
  - LV improvements/switching/remote control/switching
  - Generation retrofits include ATS breakers, synchronizing, control upgrades, communications
  - New generation includes foundation/switchgear/controls/communications/fuel tank
  - Other project costs elements include centralized control, PCC, overhead/contingency/etc.

# PRM Analysis Basics

- Uses System Adequacy Assessment (SAA) from bulk transmission analysis
  - A form of Sequential Monte Carlo (SMC) simulation
  - System is simulated through long timeframes (possibly millennia) including random effects (like equipment outages, resource availability, etc.)
  - Statistics are collected and used to infer performance over shorter time frames
- Currently included:
  - Event-driven timeline and basic statistical analysis (averages)
  - Generator start failures and unforced outages once running
  - Electrical node and branch connectivity (without outages)
  - Effects/improvements for additional generation, load, or branches
  - Renewable energy inputs
  - Load hourly and seasonal variation
- SPIDERS also includes:
  - Outages for electrical branches
  - Meta-heuristic optimization

# Analysis Assumptions

- Considered several microgrid assumptions:
  - The whole site
  - Each of the three major feeders
- Generator options – Single microgrid
  - Retrofit all existing generators > 200 kW
  - 2 x 1000 kW
  - 3 x 1000 kW
  - 3 x 750 kW
  - 4 x 750 kW
  - 4 x 500 kW
  - 5 x 500 kW
  - 6 x 500 kW
- Generator options – Three microgrid Solution
  - 7 x 500 kW
  - 5 x 500 kW and 3 x 250 kW
- Critical load estimation based on site load and transformer ratings
- Outage rates are the same as IEEE Gold Book
- Simplified PRM uses hourly time decimation

# PRM Analysis Characteristics

- Simulation time is strictly limited to 10000 years
- Minimum number of utility outage occurrences is 200
- Minimum number of outage samples with CLNS is 50
- Utility outage interval is 72 hours (per the DBT)
- The individual start probability of the generators is either 0.99 or 0.95
- The solution tolerance is 0.007 for a stop criteria using the F-CCLNS metric
- Generator MTTF is 70931 hours, and the MTTR is 18.28 hours
- The load variability follows the IEEE RTS-96 variation for the 8760 hourly intervals in the year
- PV variability follows the TMY-3 data from the NREL website

# PRM Analysis Metrics

- Critical Load Frequency of Interruption (CFOI)
- Fractional Conditional Critical Load Not Served (F-CCLNS)
- Fractional Primary Load Served per DBT interval (F-PLSD)
- Fractional PV Energy Used Per DBT interval (F-PVUD)
- Costs

# PRM Results

| Solution Type | Case | Generator Start Probability | Generator Purchase or Upgrade | CFOI | F-CCLNS | F-PLSD | F-PVUD | Total Estimated Costs |
|---|---|---|---|---|---|---|---|---|
| Base Case | BC2 | 95% | None | 0.369718 | 0.037856 | 0.7852 | N/A | $- |
| Base Case | BC3 | 99% | None | 0.096544 | 0.035588 | 0.7901 | N/A | $- |
| Single Microgrid | 1MG1 | 95% | Existing>200 | 0.009463 | 0.006584 | 0.9936 | 0.9999 | $4,182,500 |
| Single Microgrid | 1MG2 | 95% | 2 x 1000 kW | 0.089727 | 0.037007 | 0.9725 | 0.9995 | $4,200,000 |
| Single Microgrid | 1MG4 | 95% | 3 x 750 kW | 0.014775 | 0.013203 | 0.9902 | 0.9998 | $4,471,250 |
| Single Microgrid | 1MG6 | 95% | 4 x 500 kW | 0.017538 | 0.019258 | 0.9800 | 0.9998 | $4,567,500 |
| Three Microgrid | 3MG2 | 95% | 5 x 500 kW, 3 x 250 kW | 0.012870 | 0.018629 | 0.9980 | 0.4937 | $4,716,250 |
| Three Microgrid | 3MG3 | 99% | 5 x 500 kW, 3 x 250 kW | 0.001072 | 0.004331 | 0.9996 | 0.4940 | $4,716,250 |
| Single Microgrid | 1MG3 | 95% | 3 x 1000 kW | 0.005221 | 0.023843 | 0.9989 | 0.9999 | $4,733,750 |
| Single Microgrid | 1MG5 | 95% | 4 x 750 kW | 0.001580 | 0.010819 | 0.9994 | 0.9999 | $4,917,500 |
| Single Microgrid | 1MG7 | 95% | 5 x 500 kW | 0.002373 | 0.008457 | 0.9986 | 0.9999 | $4,926,250 |
| Single Microgrid | 1MG8 | 95% | 6 x 500 kW | 0.000101 | 0.004720 | 0.9999 | 0.9999 | $5,285,000 |
| Three Microgrid | 3MG1 | 95% | 7 x 500 kW | 0.017001 | 0.020247 | 0.9969 | 0.4951 | $6,046,250 |

# Recommended Microgrid Design

- Single microgrid configuration:
  - Use automated, remote MV and LV switches to control loads (switching loads on and off MG) and to control in-rush current
  - New generators, located near the substation
- Expected benefits include:
  - Resiliency for extended utility outage
  - 10-1000x reduction in critical load outages
  - PV energy contribution while islanded
  - Priority load service
- Next steps:
  - Finalize design, RFP
  - Cost avoidance/revenue opportunities for grid-connected operation
  - Applications to other NASA sites

# Conclusions

- The proposed microgrid design requirements and recommendations analysis includes three phases:
  - Conceptual
  - Preliminary
  - Detailed
- Supported by four modeling activities:
  - Systems dynamics modeling (SDM)
  - Load flow models (LFM)
  - Dynamic grid models (DGM)
  - Performance – reliability modeling (PRM) enabled by TMO
- The program includes a strong cyber security foundation
- Coordination between the myriad agencies and personnel is strong (including integrators and vendors)

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# Discussion

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